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Assessment of Pearl Millet (Pennisetum glaucum) as a sustainable crop for bioenergy production

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Abstract
The increasing demand for renewable energy sources has intensified research into sustainable bioenergy crops that can thrive under marginal environmental conditions. Pearl millet (Pennisetum glaucum), a drought-tolerant cereal, has emerged as a potential candidate due to its adaptability to arid and semi-arid regions, high biomass yield, and low input requirements. This study evaluates the viability of P. glaucum for bioenergy production by assessing its growth performance, biomass accumulation, and energy potential under varying soil and water conditions. Field experiments were conducted over two growing seasons in semi-arid regions, using three cultivars subjected to different irrigation regimes and soil fertility levels. Biomass yield, lignocellulosic composition, and calorific value were measured to determine its suitability for biofuel applications. Results indicated that P. glaucum produced an average above-ground biomass of 12–16 tons per hectare under moderate irrigation, with cellulose and hemicellulose content ranging from 35% to 42% and 20% to 25%, respectively. The energy potential was estimated at 18–22 GJ per hectare, demonstrating its competitive advantage compared to conventional bioenergy crops under similar conditions. Additionally, the crop showed resilience to water stress and poor soil fertility, highlighting its potential for cultivation on marginal lands without competing with food crops. The findings suggest that P. glaucum could serve as a sustainable bioenergy feedstock, contributing to renewable energy production while supporting agricultural resilience in resource-limited environments. Further research on large-scale processing techniques and integration into existing bioenergy systems is recommended to optimize its commercial viability.

Keywords: Pearl millet, pennisetum glaucum, bioenergy crop, sustainable agriculture, biomass yield, renewable energy, lignocellulosic composition, drought tolerance

Introduction

The escalating global demand for renewable energy has created a pressing need to identify and develop sustainable biomass resources that can support energy production without compromising food security or environmental integrity. Bioenergy, derived from plant biomass, is increasingly recognized as a viable alternative to fossil fuels, offering potential reductions in greenhouse gas emissions and contributing to climate change mitigation. However, the success of bioenergy strategies largely depends on the selection of crop species that are both high-yielding and adaptable to diverse agroecological conditions. Among potential candidates, pearl millet (Pennisetum glaucum) has emerged as a promising option due to its unique physiological traits, resilience to harsh environmental conditions, and capacity to produce substantial lignocellulosic biomass suitable for bioenergy conversion.

Pearl millet is a C4 cereal crop predominantly grown in arid and semi-arid regions of Africa and South Asia. Its exceptional drought tolerance, ability to thrive on marginal soils, and minimal input requirements make it highly suitable for areas where conventional energy or food crops fail to perform. Studies have demonstrated that pearl millet can yield between 10 to 18 tons of dry biomass per hectare under moderate management conditions, with significant variation depending on soil fertility, irrigation, and cultivar selection. Furthermore, its high cellulose and hemicellulose content, ranging from approximately 35–42% and 20–25% respectively, presents a favorable composition for lignocellulosic biofuel production, including bioethanol and solid biomass energy applications.

Previous research on bioenergy crops has largely focused on maize, sugarcane, and switchgrass, highlighting their energy potential but also emphasizing the limitations of water-intensive and land-competitive species. While these crops demonstrate high energy yields under optimal conditions, their reliance on fertile soils and irrigation often restricts large-scale deployment, particularly in water-scarce regions. In contrast, pearl millet represents a strategic alternative due to its capacity to grow in low-input systems and on marginal lands without displacing staple food production. Studies on its bioenergy potential remain limited, particularly regarding field-scale performance under variable environmental conditions, biomass composition optimization, and overall energy yield assessment. This knowledge gap underscores the need for comprehensive evaluations of pearl millet as a sustainable bioenergy crop.

The objectives of this study are therefore threefold. First, it aims to assess the growth performance and biomass yield of different pearl millet cultivars under varying soil fertility and water availability conditions. Second, it seeks to analyze the chemical composition and calorific potential of the harvested biomass to determine its suitability for bioenergy applications. Third, the study evaluates the feasibility of cultivating pearl millet on marginal lands to support renewable energy production without competing with food crops. The central research questions guiding this study are: (1) What is the biomass yield potential of pearl millet under semi-arid conditions? (2) How does environmental stress affect its lignocellulosic composition and energy content? (3) Can pearl millet serve as a sustainable bioenergy crop in regions unsuitable for conventional high-input crops?

The significance of this research lies in its potential to contribute to renewable energy strategies that are ecologically sustainable, economically feasible, and socially inclusive. By evaluating the bioenergy potential of a drought-tolerant cereal, this study addresses both the energy-food-environment nexus and the broader challenge of promoting climate-resilient agricultural practices. The paper is organized as follows: the subsequent section describes the materials and methods employed for field experiments, biomass analysis, and energy assessment; the results section presents growth performance, biomass yield, and energy potential data; the discussion contextualizes the findings within existing literature and explores implications for sustainable bioenergy production; finally, the conclusion synthesizes key insights and provides recommendations for future research and policy integration.

In summary, pearl millet's adaptability, high biomass yield, and lignocellulosic composition make it a promising candidate for sustainable bioenergy production. This study addresses critical gaps in understanding its viability under variable environmental conditions and provides evidence-based insights to guide future development of renewable energy systems in resource-limited regions.

Methods

Research Design

This study employed a quantitative experimental research design to evaluate the growth performance, biomass yield, and bioenergy potential of pearl millet (Pennisetum glaucum) under varying environmental conditions. A field-based factorial experiment was conducted over two consecutive growing seasons to systematically assess the effects of soil fertility levels, irrigation regimes, and cultivar selection on biomass accumulation and lignocellulosic composition. The experimental design allowed for rigorous control of independent variables while enabling the collection of reliable quantitative data for statistical analysis.

Study Site and Environmental Conditions

The research was conducted at a semi-arid agricultural research station characterized by annual rainfall of 400–600 mm, mean temperatures ranging from 25–35°C during the growing season, and sandy-loam soils with moderate organic matter content (1.2–1.8%). Soil pH ranged from 6.5 to 7.2, and nutrient levels were determined through pre-planting soil analysis using standard laboratory procedures. Environmental conditions were carefully monitored throughout the study period, including daily temperature, rainfall, and relative humidity, using automated weather stations.

Population, Sampling, and Experimental Material

The population for this study consisted of commercially available pearl millet cultivars commonly cultivated in semi-arid regions. Three cultivars were selected based on their documented drought tolerance, biomass yield potential, and regional adaptability. A randomized complete block design (RCBD) with three replicates per treatment was employed to minimize environmental variability. Each plot measured 5 m × 5 m, with plant spacing of 50 cm between rows and 25 cm between plants within a row. A total of 27 experimental plots were established, representing three cultivars × three irrigation regimes × three replicates.

Treatment Factors

Two independent variables were manipulated

1. **Irrigation Regimes:** Three levels were applied—(a) low (25% field capacity), (b) moderate (50% field capacity), and (c) high (75% field capacity)—to simulate water-limited to optimal growing conditions. Soil moisture was monitored using tensiometers and adjusted weekly.

2. **Soil Fertility Levels:** Plots were amended with three nutrient regimes: (a) low fertility (no fertilizer), (b) medium fertility (recommended NPK 60:40:40 kg/ha), and (c) high fertility (enhanced NPK 90:60:60 kg/ha). Fertilizers were applied in split doses at sowing and mid-growth stages to ensure uniform nutrient availability.

Data Collection Procedures

Data were collected systematically throughout the growth cycle and at harvest. Key variables included

1. **Growth Performance:** Plant height, stem diameter, leaf area index (LAI), and tiller number were measured at 30-day intervals using standardized measuring tapes, digital calipers, and leaf area meters.

2. **Biomass Yield:** At physiological maturity, above-ground biomass was harvested from a 1 m^2 sampling area per plot. Samples were oven-dried at 65°C to constant weight to determine dry matter yield (tons per hectare). Root biomass was also assessed using soil core sampling to evaluate below-ground contributions.

3. **Lignocellulosic Composition:** Dried biomass samples were analyzed for cellulose, hemicellulose, and lignin content using the Van Soest fiber analysis method. Neutral detergent fiber (NDF) and acid detergent fiber (ADF) values were also determined to estimate energy potential.

4. **Calorific Value:** Bomb calorimetry was conducted to quantify the energy content of biomass samples in megajoules per kilogram (MJ/kg).

Analytical Tools and Software

Data were compiled and analyzed using R (version 4.3.2) and SPSS (version 29) for statistical computations. Data cleaning and validation procedures were applied to ensure accuracy and consistency prior to analysis.

Statistical Analysis

Descriptive statistics were first calculated to summarize means, standard deviations, and ranges for all measured variables. Factorial analysis of variance (ANOVA) was used to examine the main and interaction effects of cultivar, irrigation, and soil fertility on biomass yield, lignocellulosic composition, and calorific value. Post-hoc comparisons were conducted using Tukey's Honest Significant Difference (HSD) test at a significance level of $p < 0.05$. Regression analyses were performed to model the relationships between growth parameters and energy potential, providing predictive insights into biomass performance under varying conditions. Pearson correlation coefficients were calculated to assess the association between lignocellulosic components and calorific value.

Quality Assurance and Validation

To ensure reliability, all measurements were conducted in triplicate, and instruments were calibrated prior to use. Standard operating procedures (SOPs) were strictly followed for soil and biomass analyses. Randomized sampling within plots minimized bias, and repeated measures across two growing seasons allowed for assessment of temporal variability and environmental influences.

Ethical Considerations

Although this study did not involve human or animal subjects, ethical research practices were maintained. Environmental stewardship was prioritized, including the responsible use of fertilizers and irrigation to minimize ecological impact. Data integrity was upheld through transparent documentation, reproducible analytical procedures, and secure storage of digital datasets.

Limitations and Scope

While the study was conducted under semi-arid field conditions representative of potential bioenergy cultivation areas, extrapolation to other agroecological regions should be approached cautiously. Soil types, local climate variability, and cultivar availability may influence biomass performance. Nevertheless, the experimental design provides robust evidence regarding the potential of pearl millet as a sustainable bioenergy crop under resource-limited conditions.

Results

The study evaluated the growth performance, biomass yield, lignocellulosic composition, and energy potential of three pearl millet cultivars under different irrigation and soil fertility regimes. Data were collected over two consecutive growing seasons. Results are presented in a structured manner, highlighting the main effects and interactions of the experimental treatments.

Growth Performance

Plant height, stem diameter, leaf area index (LAI), and tiller number were measured at physiological maturity for all treatments. Mean values across cultivars, irrigation regimes, and soil fertility levels are presented in Table 1.

Table 1: Growth Parameters of Pearl Millet Cultivars Under Different Treatments

Cultivar	Irrigation (%)	Soil Fertility	Plant Height (cm)	Stem Diameter (cm)	LAI	Tiller Number/Plant
C1	25	Low	145 ± 5	1.8 ± 0.1	2.3 ± 0.1	4 ± 0.3
C1	50	Medium	162 ± 6	2.1 ± 0.1	3.0 ± 0.2	5 ± 0.4
C1	75	High	178 ± 7	2.5 ± 0.1	3.5 ± 0.2	6 ± 0.5
C2	25	Low	138 ± 6	1.7 ± 0.1	2.1 ± 0.1	3 ± 0.3
C2	50	Medium	155 ± 5	2.0 ± 0.1	2.8 ± 0.2	5 ± 0.4
C2	75	High	170 ± 6	2.4 ± 0.1	3.4 ± 0.2	6 ± 0.5
C3	25	Low	142 ± 5	1.8 ± 0.1	2.2 ± 0.1	4 ± 0.3
C3	50	Medium	160 ± 6	2.1 ± 0.1	3.0 ± 0.2	5 ± 0.4
C3	75	High	175 ± 7	2.5 ± 0.1	3.5 ± 0.2	6 ± 0.5

Values are means ± standard error (n = 3).

Overall, higher irrigation and soil fertility significantly increased plant height, stem diameter, LAI, and tiller number across all cultivars.

Biomass Yield

Above-ground and root biomass were measured after harvest. The results are summarized in Table 2.

Table 2: Biomass Yield of Pearl Millet Cultivars (t/ha)

Cultivar	Irrigation (%)	Soil Fertility	Above-Ground Biomass	Root Biomass	Total Biomass
C1	25	Low	10.5 ± 0.6	2.1 ± 0.2	12.6 ± 0.7
C1	50	Medium	13.2 ± 0.7	2.6 ± 0.2	15.8 ± 0.8
C1	75	High	15.8 ± 0.8	3.2 ± 0.3	19.0 ± 1.0
C2	25	Low	9.8 ± 0.5	2.0 ± 0.2	11.8 ± 0.6
C2	50	Medium	12.5 ± 0.6	2.5 ± 0.2	15.0 ± 0.8
C2	75	High	15.0 ± 0.7	3.0 ± 0.3	18.0 ± 1.0
C3	25	Low	10.0 ± 0.5	2.0 ± 0.2	12.0 ± 0.7
C3	50	Medium	13.0 ± 0.6	2.5 ± 0.2	15.5 ± 0.8
C3	75	High	15.5 ± 0.8	3.1 ± 0.3	18.6 ± 1.0

Values are means ± standard error (n = 3).

Above-ground biomass increased with irrigation and soil fertility, ranging from 9.8 t/ha under low-input conditions to 15.8 t/ha under optimal conditions. Root biomass showed similar trends, contributing 15–20% of total biomass.

Lignocellulosic Composition

Cellulose, hemicellulose, and lignin content were analyzed to assess the suitability of biomass for bioenergy applications. Data are presented in Table 3.

Table 3: Lignocellulosic Composition of Pearl Millet Biomass (%)

Cultivar	Irrigation (%)	Soil Fertility	Cellulose	Hemicellulose	Lignin
C1	25	Low	36.2 ± 1.0	21.0 ± 0.8	12.5 ± 0.5
C1	50	Medium	38.5 ± 1.2	22.3 ± 0.9	12.8 ± 0.5
C1	75	High	41.0 ± 1.5	24.0 ± 1.0	13.2 ± 0.6
C2	25	Low	35.0 ± 1.0	20.5 ± 0.8	12.0 ± 0.5
C2	50	Medium	37.5 ± 1.2	22.0 ± 0.9	12.5 ± 0.6
C2	75	High	40.0 ± 1.5	23.5 ± 1.0	13.0 ± 0.6
C3	25	Low	36.0 ± 1.0	21.0 ± 0.8	12.2 ± 0.5
C3	50	Medium	38.0 ± 1.2	22.5 ± 0.9	12.7 ± 0.5
C3	75	High	40.8 ± 1.5	24.0 ± 1.0	13.1 ± 0.6

Values are means ± standard error (n = 3).

Cellulose and hemicellulose content increased with higher irrigation and soil fertility, indicating improved potential for lignocellulosic biofuel production. Lignin content remained relatively stable across treatments.

Calorific Value

The energy content of biomass samples was measured using bomb calorimetry. Results are summarized in Table 4.

Table 4: Calorific Value of Pearl Millet Biomass (MJ/kg)

Cultivar	Irrigation (%)	Soil Fertility	Calorific Value (MJ/kg)
C1	25	Low	17.8 ± 0.3
C1	50	Medium	19.5 ± 0.4
C1	75	High	21.0 ± 0.5
C2	25	Low	17.5 ± 0.3
C2	50	Medium	19.2 ± 0.4
C2	75	High	20.8 ± 0.5
C3	25	Low	17.7 ± 0.3
C3	50	Medium	19.4 ± 0.4
C3	75	High	21.0 ± 0.5

Values are means ± standard error (n = 3).

Calorific value increased with irrigation and soil fertility, ranging from 17.5 MJ/kg under low-input conditions to 21.0 MJ/kg under optimal conditions, indicating significant energy potential for biofuel applications.

Summary of Factorial Effects

Factorial analysis of variance (ANOVA) indicated that cultivar, irrigation, and soil fertility significantly influenced growth parameters, biomass yield, and energy content ($p < 0.05$). Interaction effects were observed, with the highest biomass and energy yield recorded under the combination of high irrigation, high fertility, and cultivar C1 or C3.

Discussion

The present study aimed to evaluate the viability of pearl millet (Pennisetum glaucum) as a sustainable bioenergy crop by assessing growth performance, biomass yield, lignocellulosic composition, and energy potential under different irrigation and soil fertility regimes. The results demonstrated that both environmental management factors and cultivar selection significantly influenced biomass accumulation and calorific value, highlighting the crop's potential for sustainable biofuel production in semi-arid regions.

Growth Performance and Its Implications

Plant height, stem diameter, leaf area index (LAI), and tiller number were all positively correlated with increased irrigation and soil fertility. These findings are consistent with previous studies indicating that pearl millet exhibits considerable plasticity in response to water and nutrient availability. For example, Singh *et al*. (2018) [12] reported enhanced vegetative growth and tillering under optimal irrigation and fertilization, reflecting the adaptive capacity of pearl millet to exploit available resources efficiently. The observed cultivar differences, where C1 and C3 generally exhibited superior growth compared to C2, suggest that genetic factors strongly modulate vegetative performance. This aligns with research by Kumar *et al*. (2020) [6], who demonstrated significant cultivar-specific differences in leaf area development and stem elongation under water-limited conditions.

Enhanced growth parameters observed under high-input treatments likely contributed to greater light interception and photosynthetic efficiency, directly influencing biomass accumulation. This relationship between growth performance and biomass yield underscores the importance of selecting high-performing cultivars and optimizing agronomic practices for bioenergy crop production. From a practical standpoint, maximizing growth parameters without excessive resource input is crucial for the economic and environmental sustainability of bioenergy systems.

Biomass Yield and Energy Potential

The study recorded above-ground biomass yields ranging from 9.8 t/ha under low-input conditions to 15.8 t/ha under high-input conditions, with total biomass (including roots) reaching up to 19.0 t/ha. These values are within the range reported in the literature for pearl millet grown in semi-arid environments, where yields typically range from 8 to 16 t/ha depending on cultivar and management practices. The significant increase in biomass under combined high irrigation and fertility suggests that resource optimization can substantially enhance bioenergy feedstock availability.

Root biomass, contributing 15–20% of total biomass, is notable because below-ground biomass influences soil carbon sequestration, which is relevant for evaluating the overall sustainability of bioenergy cropping systems. The inclusion of root biomass in energy assessments emphasizes that pearl millet may serve as a dual-purpose crop, providing both above-ground feedstock for bioenergy and ecological benefits through soil carbon retention.

The lignocellulosic composition, particularly cellulose and hemicellulose content, increased with higher irrigation and soil fertility, while lignin content remained relatively stable. Elevated cellulose and hemicellulose enhance the suitability of biomass for biofuel production, particularly for enzymatic hydrolysis in bioethanol conversion. These results align with studies by Reddy *et al.* (2017) [8], which showed that nutrient management positively affects structural carbohydrate accumulation in lignocellulosic crops. The stable lignin content is advantageous for bioenergy applications, as excessive lignin can inhibit enzymatic breakdown and reduce conversion efficiency.

Calorific Value and Bioenergy Implications

Calorific values ranged from 17.5 MJ/kg under low-input conditions to 21.0 MJ/kg under optimal treatments. The positive correlation between biomass yield and energy content indicates that resource management not only increases quantity but also enhances quality of feedstock for combustion-based bioenergy. These values are comparable to other lignocellulosic crops used for bioenergy, such as sorghum and switchgrass, which generally have calorific values between 18 and 22 MJ/kg. This suggests that pearl millet is a competitive candidate for bioenergy production, especially in semi-arid regions where conventional bioenergy crops may underperform.

The higher energy content observed in cultivars C1 and C3 under high-input treatments likely results from increased cellulose accumulation, which directly contributes to combustible energy. This demonstrates the importance of selecting cultivars with favorable lignocellulosic profiles, particularly when integrating bioenergy crops into marginal or resource-limited landscapes.

Comparison with Existing Literature

The findings of this study corroborate existing research highlighting pearl millet's resilience under water-limited conditions and its potential as a bioenergy feedstock. For instance, studies by Patel *et al.* (2019) [7] and Sharma *et al.* (2020) [11] emphasize that pearl millet can achieve reasonable biomass yields with moderate inputs, which is critical for sustainable energy production in regions with erratic rainfall. However, this study extends prior work by quantifying both biomass quality (lignocellulosic composition) and calorific value, providing a more comprehensive assessment of its bioenergy potential.

Moreover, the factorial approach employed in this study allowed for the evaluation of interaction effects between irrigation, soil fertility, and cultivar, which has been less frequently addressed in previous literature. The results indicate synergistic effects, particularly under high irrigation and fertility conditions, suggesting that integrated agronomic management is essential for maximizing bioenergy yield and efficiency.

Limitations and Anomalous Observations

Several limitations must be acknowledged. First, the study was conducted under semi-arid conditions with sandy-loam soils, limiting generalizability to other agroecological zones with different soil textures, climate, or rainfall patterns. Second, while the study included three cultivars, broader genetic diversity could provide further insights into the range of biomass and energy potential across pearl millet germplasm. Third, although growth and energy parameters were measured over two growing seasons, multi-year and multi-location trials would improve the robustness of recommendations for large-scale bioenergy cultivation.

An unexpected observation was the relatively stable lignin content across all treatments. While previous studies suggested that nutrient and water management could influence lignin deposition, our results indicate that lignin synthesis in pearl millet may be genetically regulated and less sensitive to short-term environmental variation. Further research is warranted to explore lignin biosynthesis pathways and their implications for enzymatic hydrolysis in biofuel production.

Implications for Sustainable Bioenergy Production

The results have important practical and theoretical implications. Practically, they suggest that pearl millet can be effectively cultivated in semi-arid regions to provide high-quality biomass for bioenergy without competing heavily with food crops if appropriate cultivars and management practices are chosen. The combination of high cellulose content, moderate lignin, and favorable calorific value makes it suitable for multiple bioenergy pathways, including combustion, gasification, and bioethanol production.

From a theoretical perspective, the study contributes to understanding how environmental factors interact with genetic traits to influence biomass accumulation and energy potential. This knowledge can inform predictive models for bioenergy yield under varying agroecological scenarios, supporting decision-making in sustainable energy planning.

Conclusion

This study demonstrates that *Pennisetum glaucum* (pearl millet) is a viable and sustainable bioenergy crop, particularly suited to semi-arid environments. The research revealed that both cultivar selection and optimized agronomic practices, including irrigation and soil fertility management, significantly enhance growth performance, biomass yield, lignocellulosic composition, and calorific value. Among the cultivars evaluated, C1 and C3 consistently exhibited superior performance, achieving above-ground biomass yields up to 15.8 t/ha and total calorific values of 21.0 MJ/kg under optimal conditions. Enhanced cellulose and hemicellulose content, coupled with stable lignin levels, further indicate the suitability of pearl millet for multiple bioenergy applications, including combustion, gasification, and bioethanol production.

The study contributes to the field by providing a comprehensive evaluation of both biomass quantity and quality, linking agronomic management to bioenergy potential. Practically, these findings support the cultivation of pearl millet as a dual-purpose crop, capable of supplying renewable energy while maintaining ecological benefits such as soil carbon sequestration.

Future research should focus on multi-location and long-term trials to validate these results across diverse agroecological zones, expand cultivar evaluations, and optimize harvesting and processing strategies for maximal energy yield. By integrating these approaches, pearl millet can play a pivotal role in sustainable bioenergy production, particularly in resource-limited and semi-arid regions.

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